National Aeronautics and Space Administration

# Carbon-Carbon Nozzle Extension Development in Support of In-Space and Upper Stage Liquid Rocket Engines

AIAA Propulsion and Energy Forum
*July 12, 2017*
AIAA-2017-5064

***Paul R. Gradl***
***Peter G. Valentine***
*NASA Marshall*

*Paul.R.Gradl@nasa.gov*

MARSHALL
SPACE FLIGHT CENTER

# Motivation for Extension Development

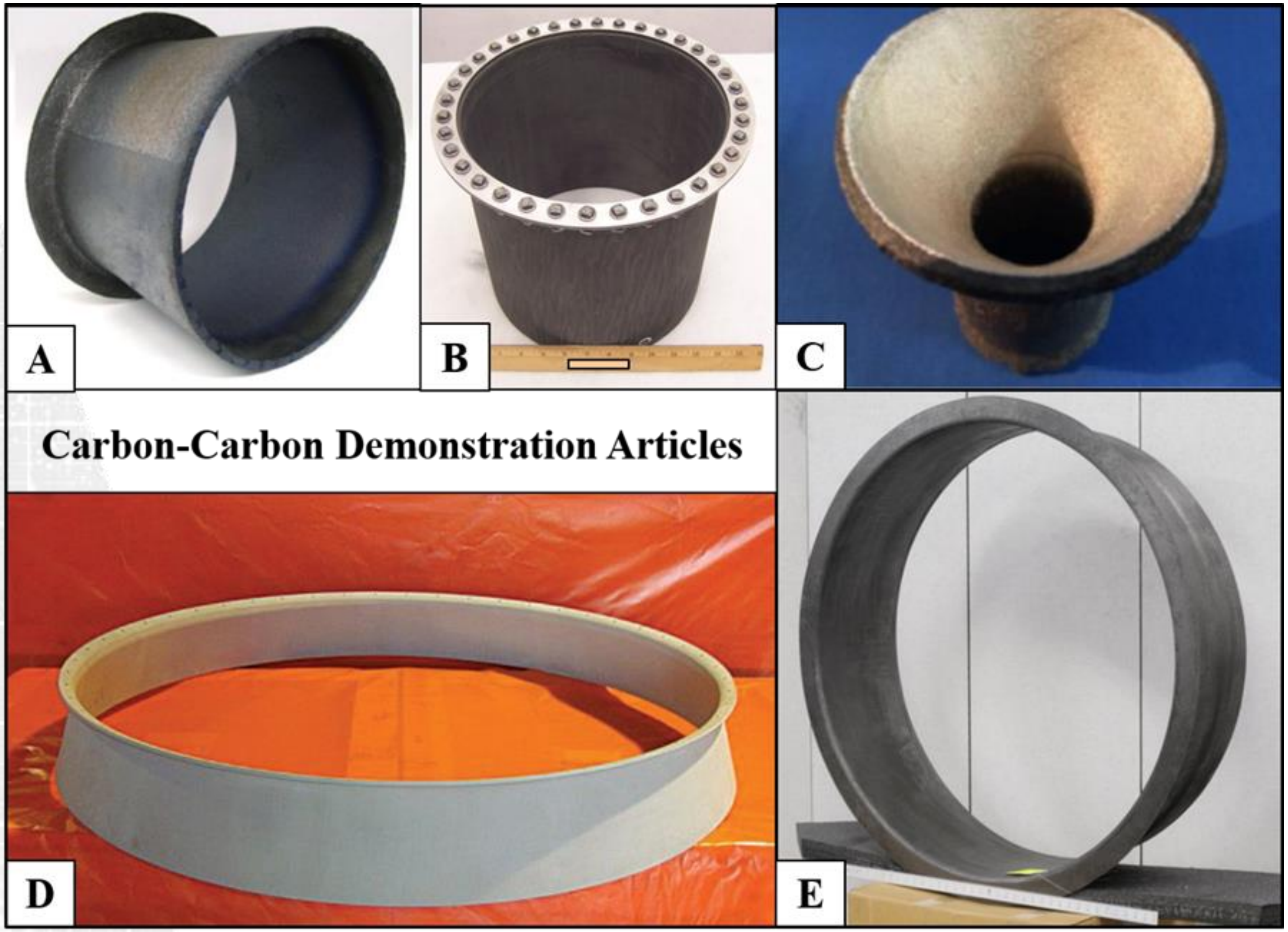
- NASA and commercial space partners are interested in developing a commercial supply chain for Carbon-Carbon Nozzle Extensions (CCNE)
- Provides significant advantages for a variety of upper-stage engines and in-space engines
  - Weight Reduction – 50% savings vs. metallic
  - Improved thermal design margins – 500-1500°F
  - Less complex designs and/or manufacturing processes
  - Cost Reduction
  - New design opportunities to further optimize regen-extension joint
- Evaluate high temperature nozzle extension fabrication processes and obtain preliminary hot-fire test data in a relevant environment to characterize materials

**Goal:** Advance the state of the U.S. Carbon-Carbon (C-C) technology to the point that domestic C-C nozzles can be considered as viable candidates for use on U.S. cryogenic upper stage engines, in-space, ascent/decent lander engines and nuclear engines

# NASA Funded Tasks – SBIR/STTR, IRAD, and Industry Partnerships

**SBIR/STTR Development**

A. **PAN-based hybrid C-ZrC/C-C**
   *Ultramet, C-CAT*
B. **Rayon-based involute C-C**
   *MR&D, Orbital ATK*
C. **PAN-based Ir-lined involute C-C**
   *MR&D, Orbital ATK, Plasma Processes*
D. **PAN-based C-C with "high-melt" and SiC coating systems**
   *C-CAT*
E. **Lyocell-based C-C**
   *C-CAT, Southern Research*

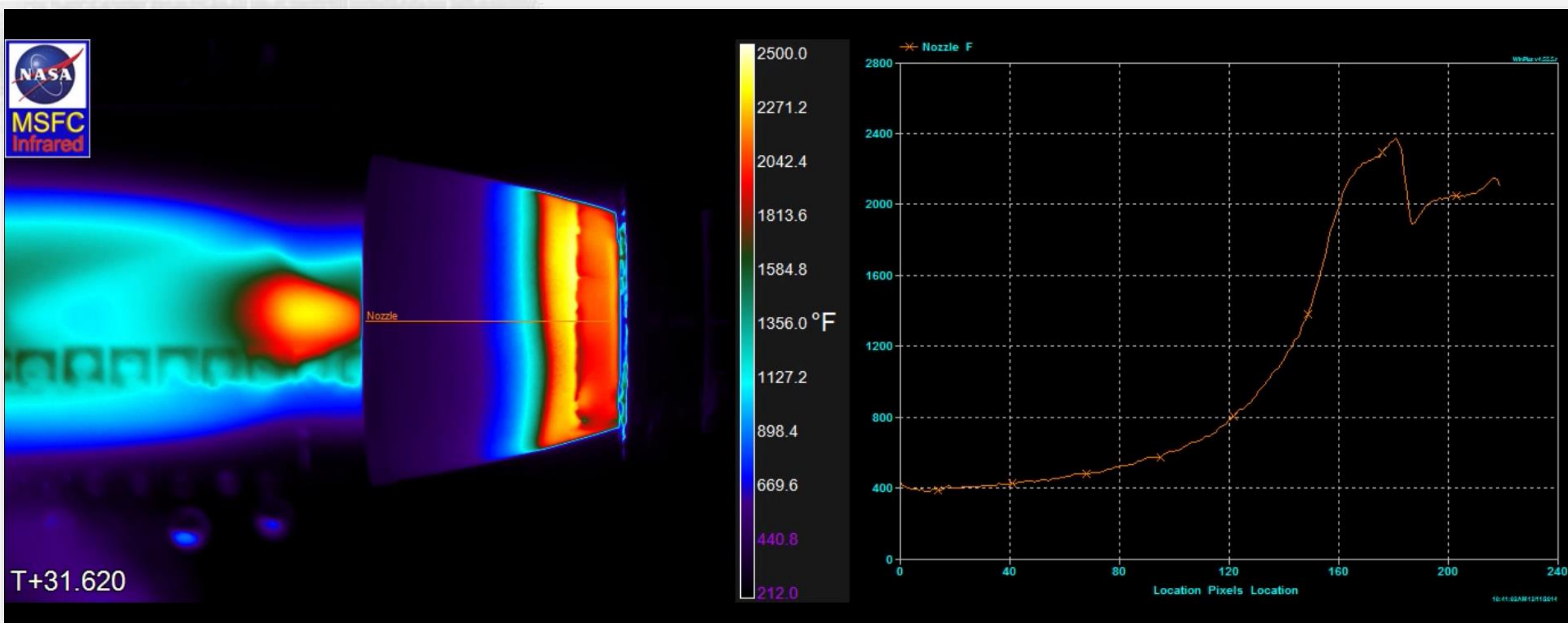



## MSFC In-House Technology Development Projects

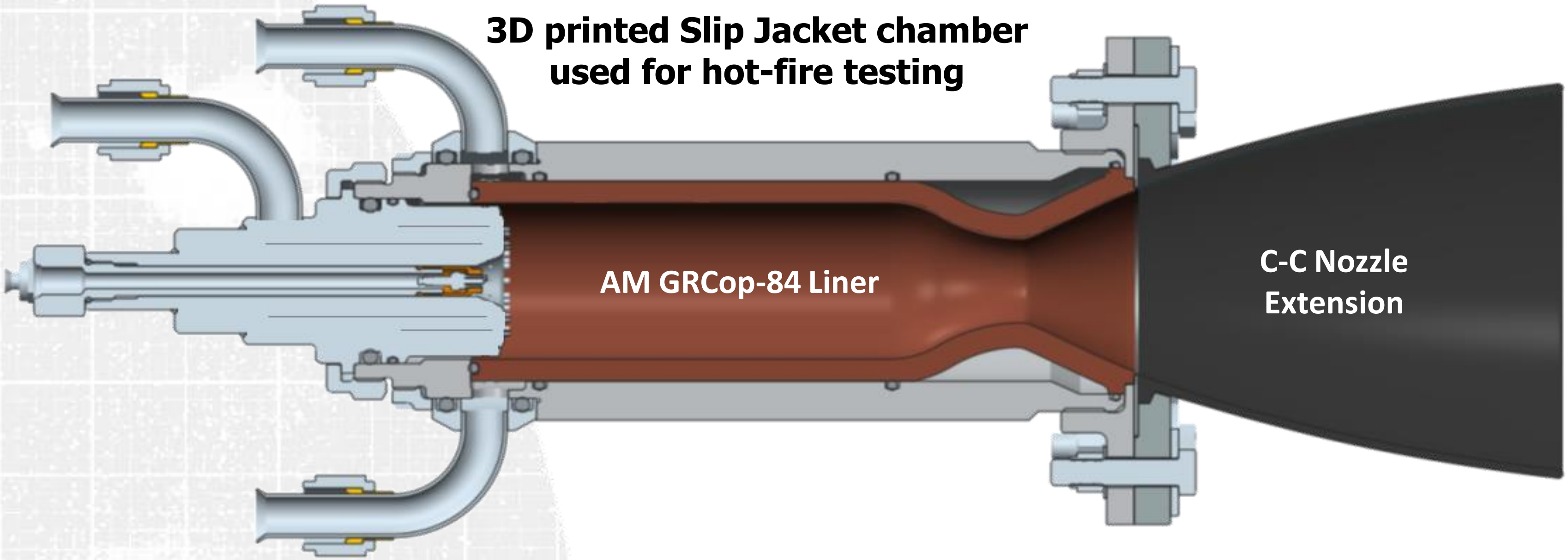
- Materials screening via 1.2K-$lb_f$ LOX/$GH_2$ small thruster testing
- Moderate-scale demonstration via 35K-$lb_f$ LOX/LH2 chamber to evaluate material feasibility
- Component and coupon level material testing

# Background of MSFC Test Rig

- Starting in 2014, MSFC created a subscale nozzle test rig to conduct affordable, long-duration hot-fire testing for NASA and commercial partners
  - LOX/GH2, LOX/CH4, or LOX/RP capabilities
  - Durations up to 180 seconds
  - Previous testing used a vintage chamber, which caused flow separation limiting the length of the nozzle



# Design of New Chamber Assembly



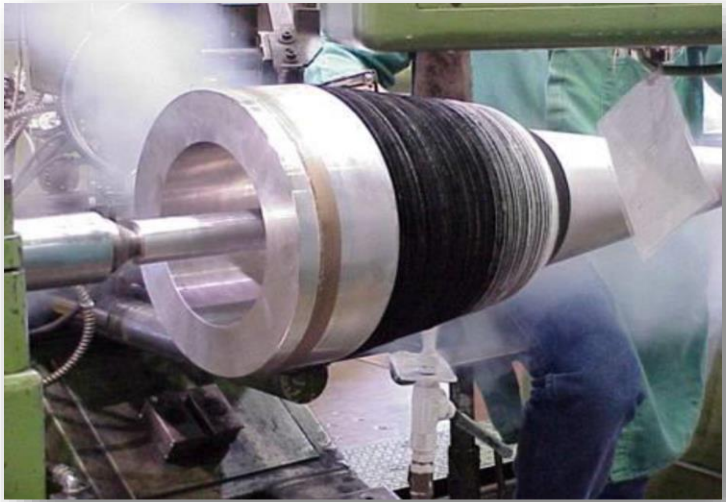

- New contour design allows for full-flow extended length nozzles and extensions
- 27:1 expansion
- Pc = 750 psig
- 1,200 $lb_f$ thrust
- Duration up to 180 sec
- Additive manufactured (AM) GRCop-84 liner

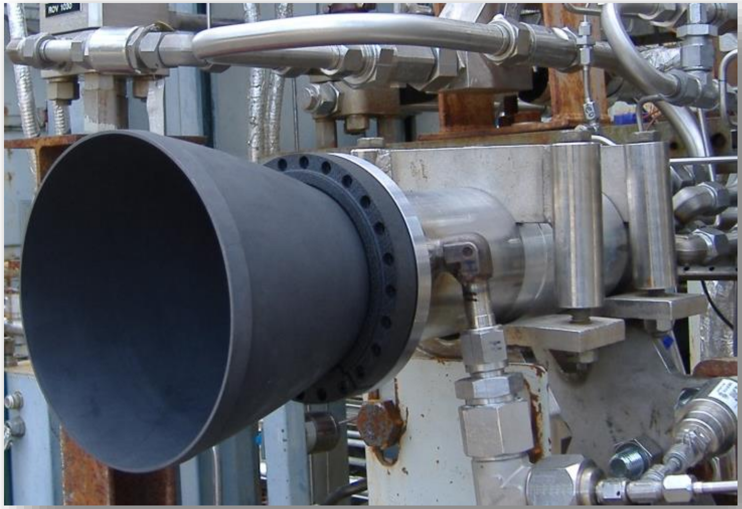
| | Heritage Design | New Design |
|---|---|---|
| Thrust Chamber Assembly, Drawing Reference | MER00060-101 | MER01446-001 |
| Main Combustion Chamber, Liner | MED04227-1 | MER00664-001 |
| Maximum Chamber Pressure, Pc (psia) | 850 | 1350 |
| Water Coolant Inlet Pressure, (psia) | 1000 | 2000 |
| Chamber Barrel Diameter (in) | 2.25 | 2.25 |
| Chamber Barrel Length (in) | 6.77 | 5.26 |
| Divergent Radius, Rd/Rt | 2 | 0.5 |
| Throat Diameter (in) | 1.2 | 1.2 |
| Nozzle Attach area ratio (AR) | 8.1:1 | 4.4:1 |

# Orbital ATK CCNE Testing at MSFC TS115

**Joint MSFC/OATK effort to demonstrate new test and material capabilities**

- Scale-up and demonstration of low cost manufacturing processes using tape wrapped preforms, a rapid densification process, and a variety of oxidation barriers.
- Static testing of extensions included:
  - Demonstration of attachment and sealing concept for 2D CCNE's
  - Demonstration of 2D C-C/oxidation-barrier systems in long duration, multiple start/stop tests. Oxidation protection systems provided by:
    - COIC -- 3 systems
    - Exothermics -- 1 system
    - Plasma Processes -- 2 systems
- Seven nozzle extensions manufactured and successfully tested in December 2014.
- Additional testing in Aug-Sep 2016.





# C-CAT CCNE Testing at MSFC TS115

**Joint MSFC / Carbon-Carbon Advanced Technologies (C-CAT) effort**

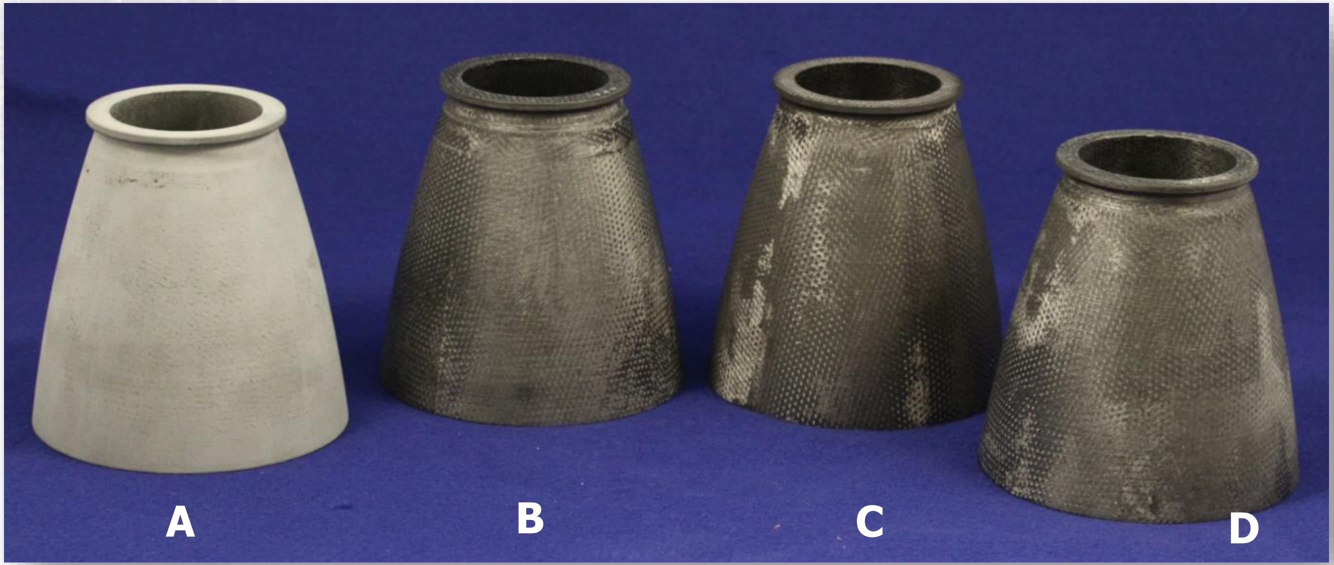
- Demonstrate SiC coated C-C, which is being considered for LOX/LH2 nozzle extension applications
- Experimental enhanced-matrix C-C (EMCC) systems that do not require use of high-cost protective coatings

**Four 2D C-C Materials Tested**

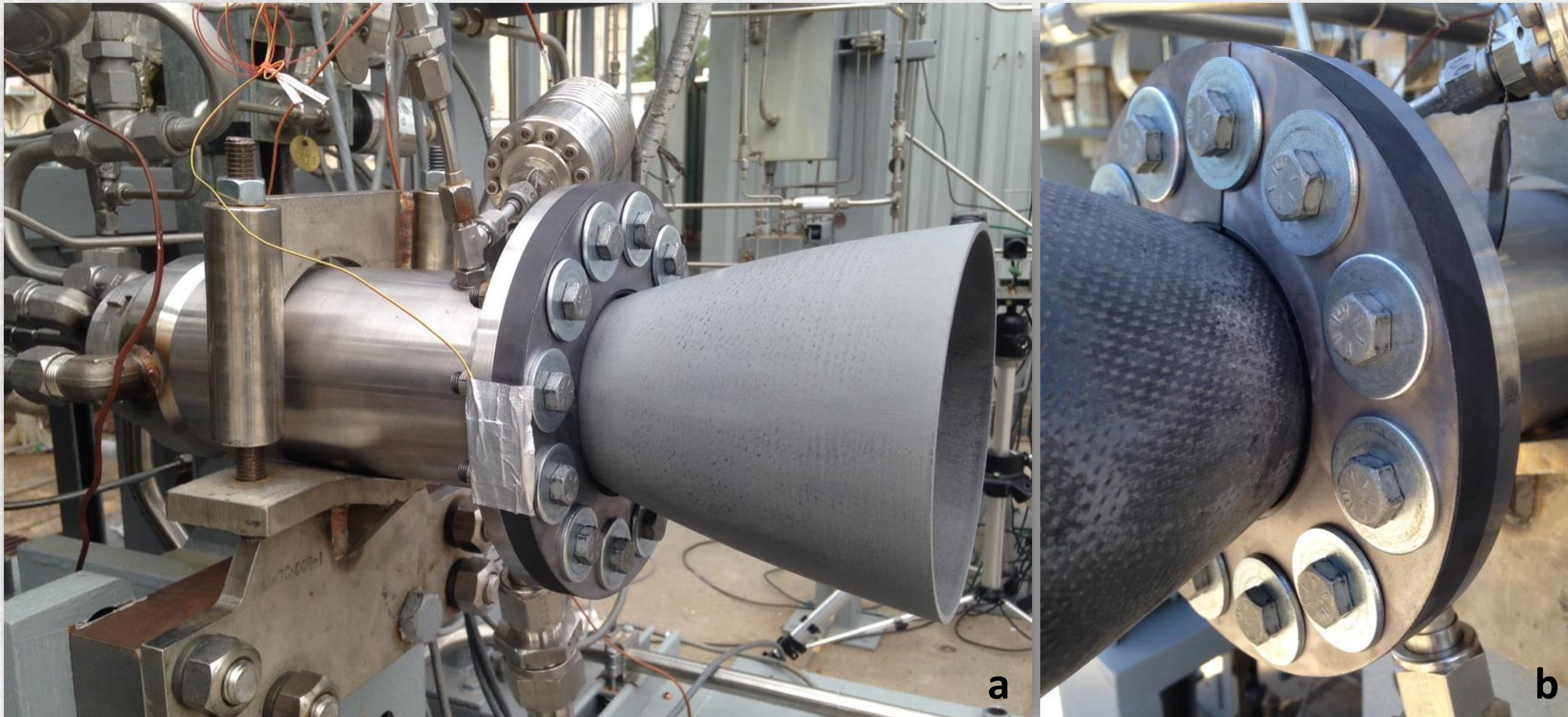
A. ACC-6 with silicon carbide (SiC) pack cementation coating
B. ACC-6 with SiC enhanced matrix – *an experimental material*
C. ACC-4 with no coating
D. ACC-6 with zirconium diboride (ZrB2) plus hafnium carbide (HfC) enhanced matrix – *an experimental material*

**CCNE's Prior to Hot-Fire Testing**

- All use T-300 PAN 3K heat treated material
- All used the same tooling.



# Extension Design and Chamber Interface (C-CAT)




**Nozzle Extension Installed on Thrust Chamber Assembly**

a. Full assembly at MSFC TS-115.
b. View of tantalum backer split ring, graphite split ring, and overall interface region.
    - C-C extensions attached to aft flange of combustion chamber using GES Graphite (PFI-25 and PFI-45) split rings.
    - Grafoil, grade GTB flexible graphite, 0.060″ thick compressed seal at interface between graphite and combustion chamber flange.
    - Tantalum split-ring backer plate at aft end of graphite split ring.

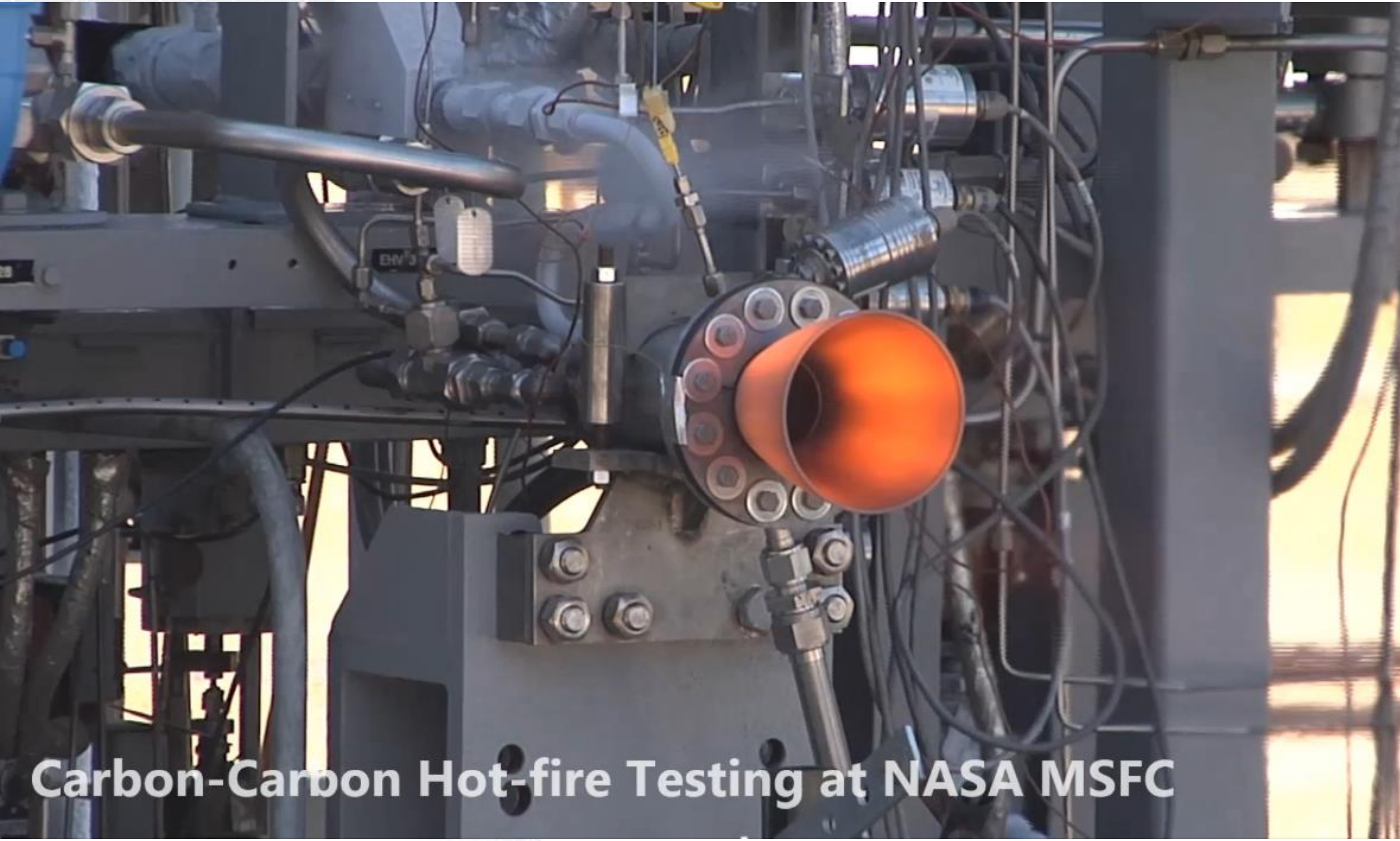
# C-C Extension Hot-fire Testing Results

Orbital ATK Extension Test with COIC SiC + Hf

C-CAT Extension Test, $ZrB_2$/HfC EMCC

| Base Material | Anti-Oxidation Protection *coating* | Accumulated Duration *sec* |
|---|---|---|
| OATK TW Rapid Densification 3 Cycles | Bare | 10 |
| OATK TW Rapid Densification 3 Cycles | COIC-SiC, No Filler | 90 |
| OATK TW Rapid Densification 3 Cycles | PPI $ZrB_2$+SiC, APS | 30 |
| OATK TW Rapid Densification 3 Cycles | Exothermics Si-Partial SiC | 155 |
| OATK TW Rapid Densification 3 Cycles | PPI $MoSi_2$-based, VPS | 30 |
| OATK TW Rapid Densification 3 Cycles | COIC-SiC + Hf-based Filler | 720 |
| OATK TW Rapid Densification 3 Cycles | COIC-SiC + Zr-based Filler | 480 |
| C-CAT 40 ACC-4 | Bare | 240 |
| C-CAT 40 ACC-6 | SiC Conversion | 2050 |
| C-CAT EMCC ACC-6 | None, SiC-enhanced resin EMCC | 10 |
| C-CAT EMCC ACC-6 | $ZrB_2$/HfC enhanced matrix EMCC | 64 |

# Video of Hot Fire Testing



# Orbital ATK Extension, COIC Hf-based filler

3 Starts, Post-120 sec

240 sec

360 sec

480 sec

600 sec

720 sec

<23% weight loss at elevated mixture ratios, although attributed to flow separation region as predicted

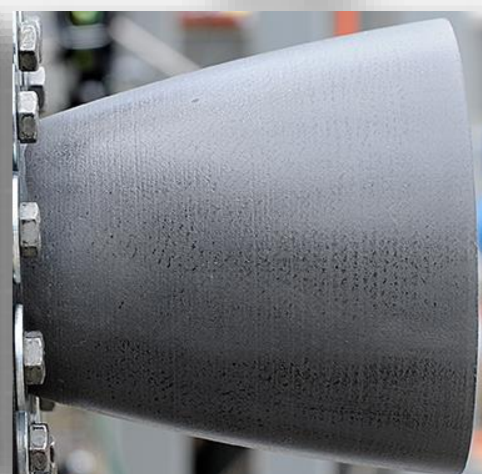
# C-CAT ACC-6 with silicon carbide (SiC) coating

Pretest

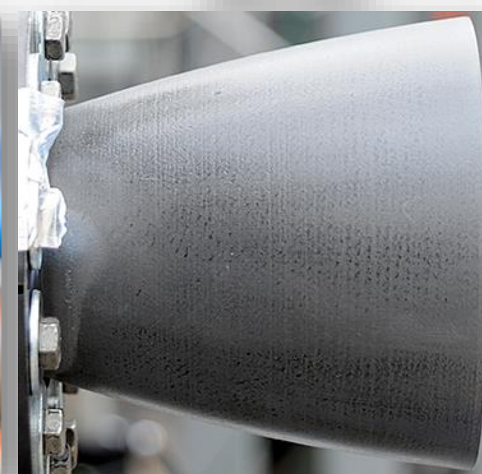
72 sec

222 sec

790 sec



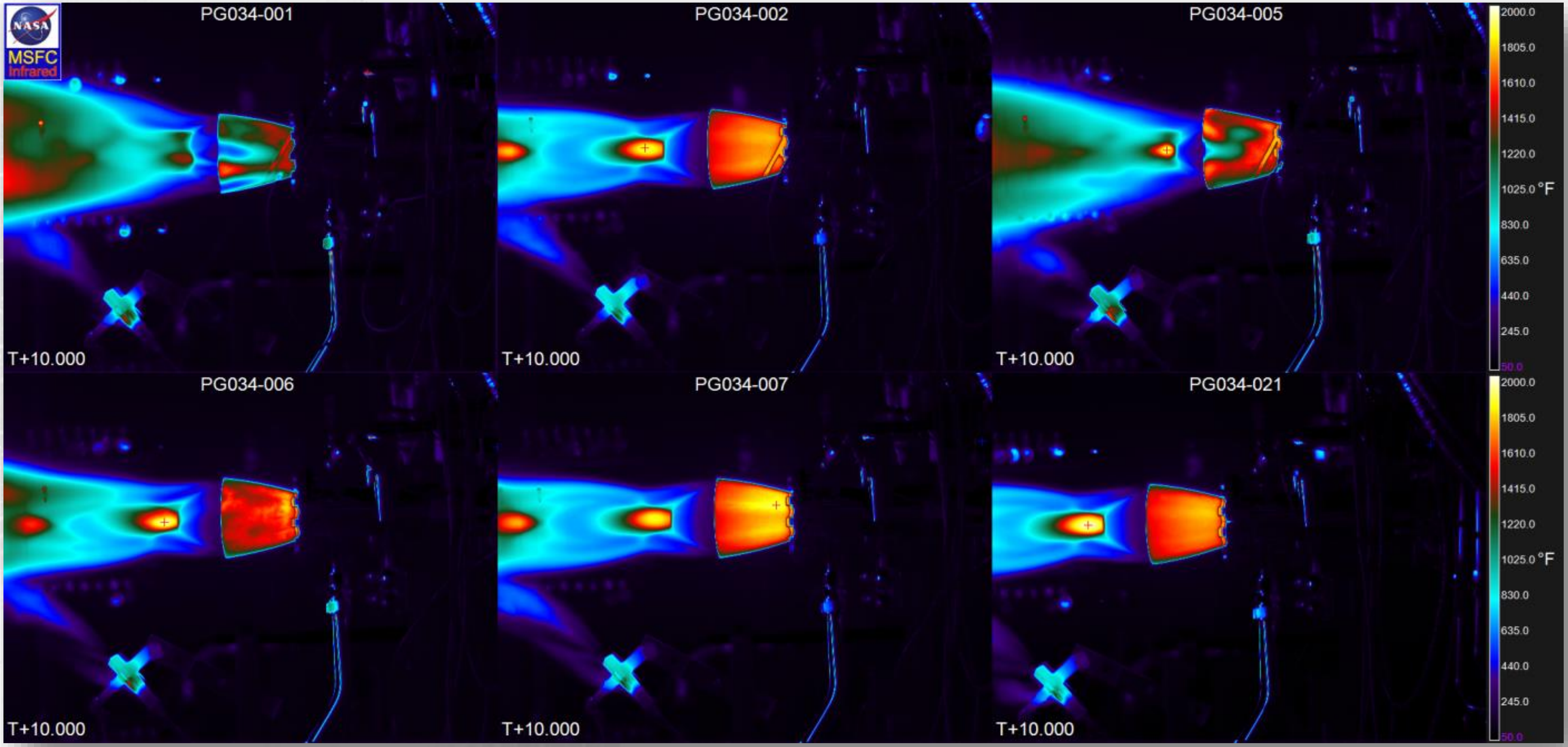
1690 sec



2050 sec

**No erosion observed on ID surface**; *Note: oxidation more prevalent on OD aft end due to entrainment flow; based on results from EMCC material and uncoated testing*

# Infrared Thermography during C-CAT Testing




**Comparison of infrared (IR) thermography imaging for C-CAT extensions at start +10 seconds with various amounts of streaking observed.**

- Ply lifts observed in EMCC
- Operated at temperatures up to 2400°F

*Note: Tests -002, -007, -021 are with the SiC conversion coating.*

# Moderate-scale C-C 35K-$lb_f$ Technology Demonstrator

**LCUSP Thrust Chamber Assembly with C-C Extension**

*LCUSP = Low Cost Upper Stage Propulsion / Fully 3D Printed Multi-metallic combustion chamber*

## Polyacrylonitrile- (PAN-) based C-C

- **T-300 3K fiber**, with heat treatment
- **ACC-6 condition**
- **Silicon carbide (SiC) coating**

*Approx. 25" diameter*

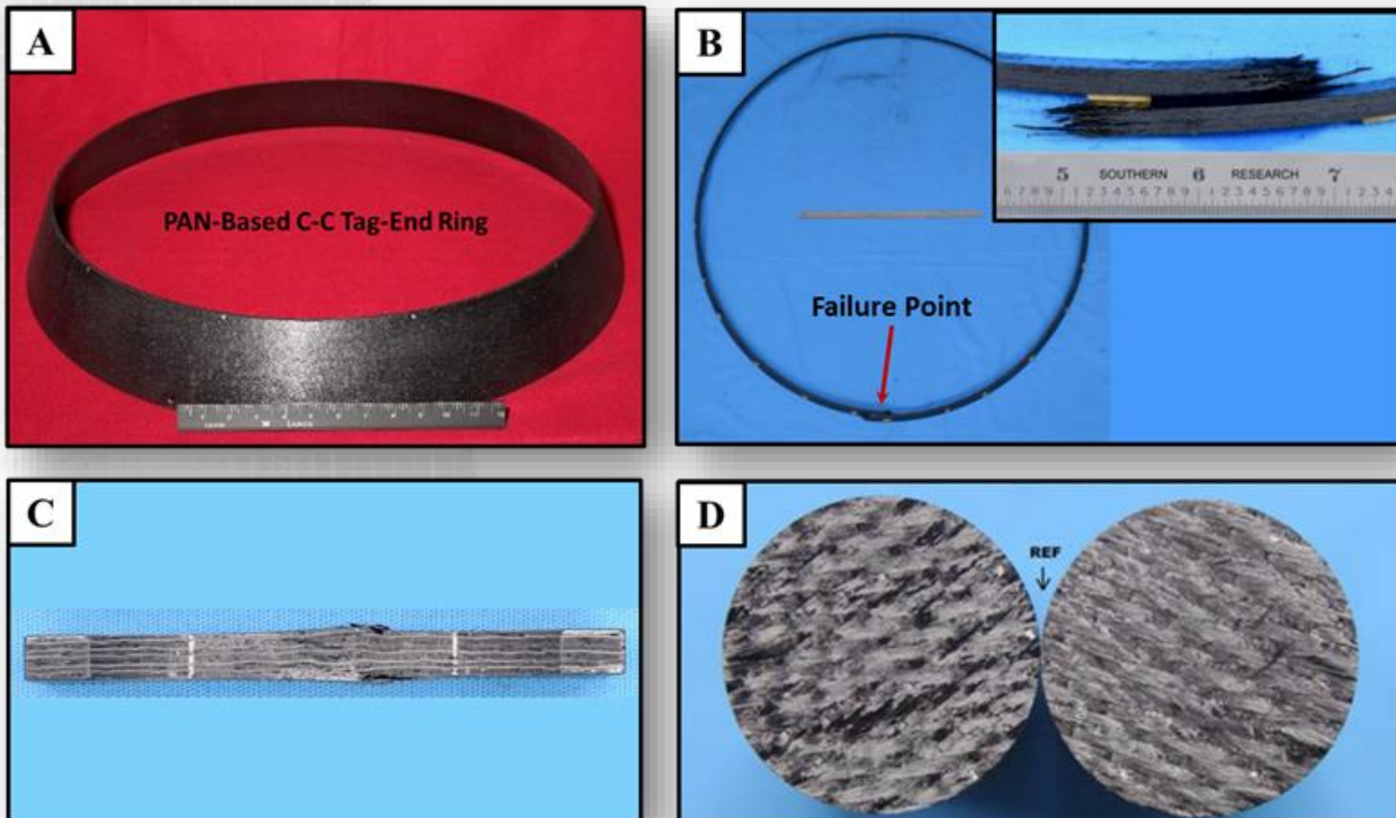
## Lyocell-based C-C

- **Lyocell fiber**, with heat treatment
- **ACC-4 condition**
- **Uncoated,** due to fiber heat treat limit

- Both extensions fabricated using the same tooling

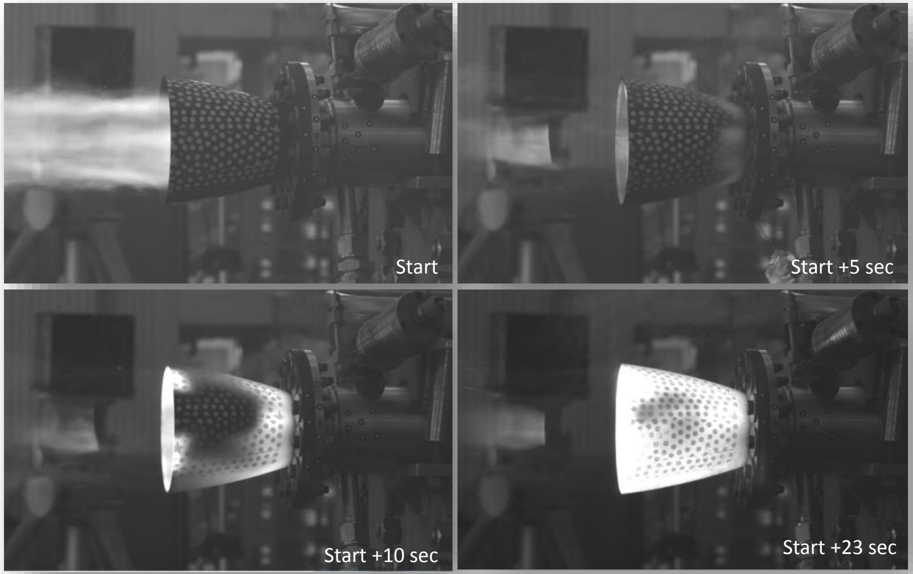
# C-C Subelement and Coupon Testing

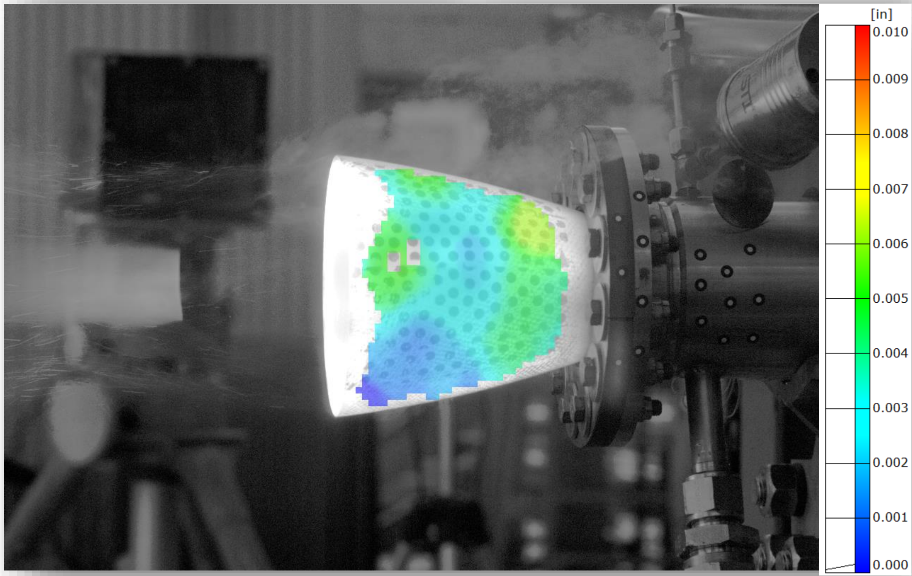
- **Tag-end rings sectioned from 35K demonstrator extensions**
  - Developed NDE techniques for C-C extensions
  - Coupon material testing (axial compression, interlaminar tension, hoop thermal expansion)
  - Hydrostatic loading of conical ring full diameter sections



# Digital Image Correlation Support C-C Development

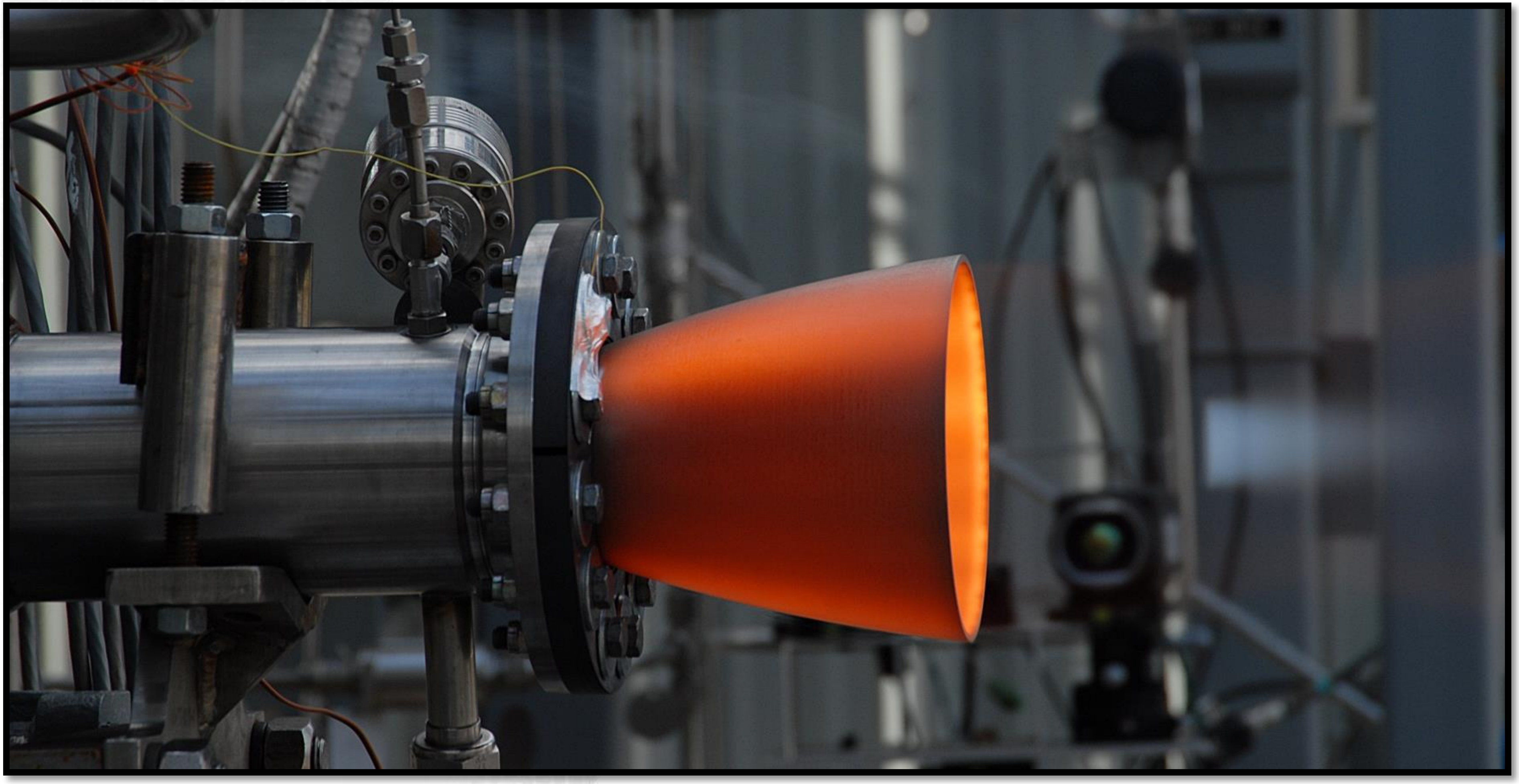
- Optical non-contact measurement development supporting C-C development
  - Using digital image correlation (DIC) to obtain full field surface strains and displacements
- Elevated temperatures during hot-fire testing using visible wavelength (DIC) caused issues during transients
  - Evaluating alternate DIC techniques such as UV-DIC
- DIC techniques have been proven during full-scale lab testing



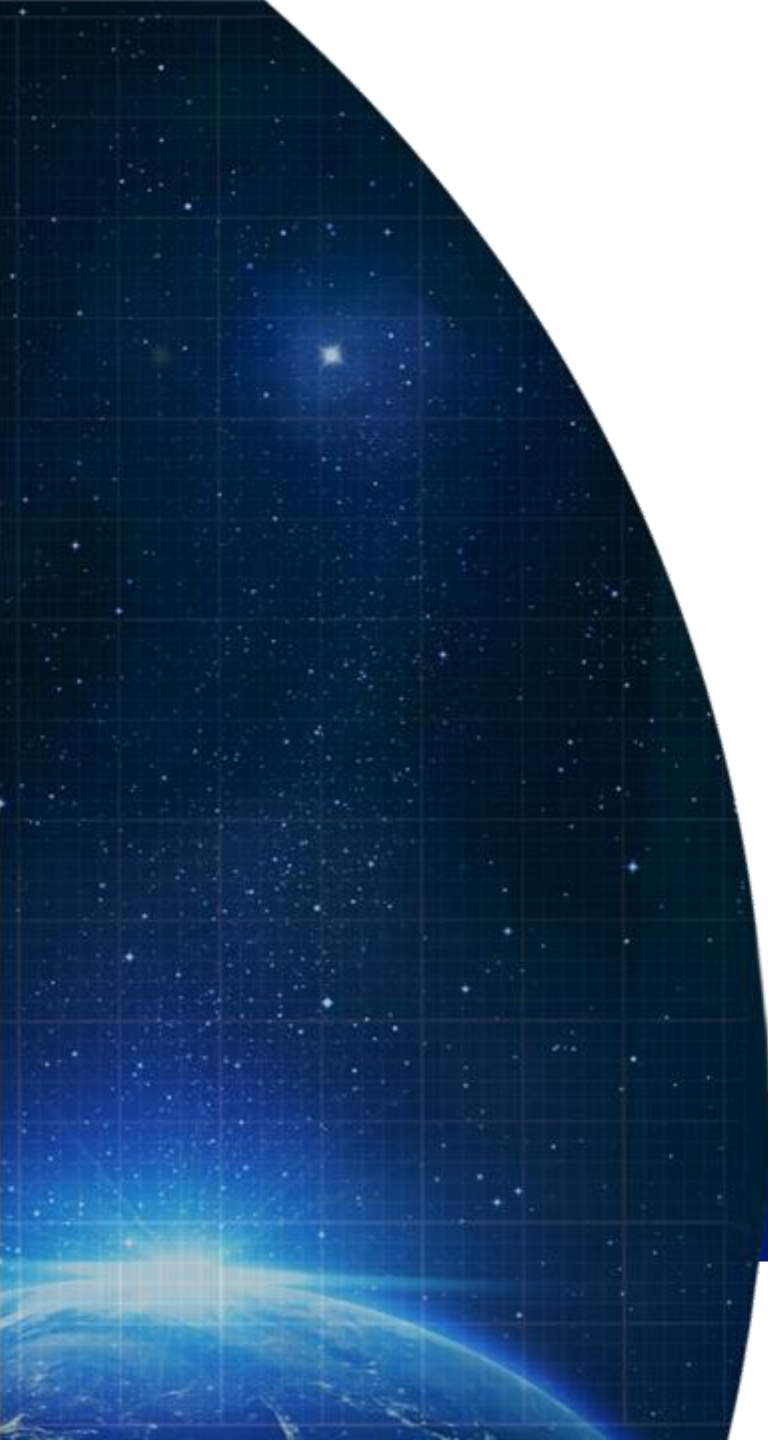
# Conclusions and Future Work

- **NASA and its commercial space partners are interested in advancing a domestic commercial supply chain for Carbon-Carbon Nozzle Extensions (CCNE's).**
- **MSFC is interested in evaluating materials appropriate for cryogenic upper stage engines and obtaining preliminary hot-fire test data in relevant environments.**
- **C-C nozzle extension efforts have proceeded primarily through the following:**
  - Small business contracts investigating: attachment concepts, material systems, etc.
  - MSFC in-house technology development projects:
    - C-C material systems, databases, advancement of technology and material readiness levels (TRL, MRL), geometry effects on properties for flat vs. complex shapes, etc.
    - Materials screening with 1.2K-$lb_f$ LOX/GH2 thruster to obtain preliminary hot-fire test data.
      - **Completed testing on variety of materials from C-CAT and Orbital ATK.**
    - Moderate-size demos via 35K-$lb_f$ LOX/LH2 engine – low-budget feasibility assessments.
- **Extended duration subscale testing has demonstrated extension and coating technology**
  - C-CAT PAN ACC-6 w/ SiC Conversion Coating = 2,050 sec hot-fire
  - Orbital ATK Tape Wrap w / COIC Hf-based filler = 720 sec hot-fire
- **NASA MSFC to complete testing of 35k-$lb_f$ truncated extensions on 3D printed copper chamber in Fall-2017**



# Acknowledgements


- Sandy Elam Greene
- Cynthia Sprader
- David Olive
- Test Stand 115 Crew
- Will Brandsmeier
- Cory Medina
- Jennifer Adams
- Ian Johnston
- Gary Kelly
- Van Luong
- Gregg Jones
- Chris Protz
- Derek Moody
- Darrell Gaddy
- Brian Sullivan / MR&D
- Leslie Weller / MR&D
- David Myers /EM20
- James Walker / EM20
- Ken Cooper
- John Fikes
- Tony Kim
- Steve Fentress /Rocketdyne
- Matt Crisanti / C-CAT
- James Thompson / C-CAT
- Aaron Brown / C-CAT
- John Shigley / OATK
- Robert Roberts / OATK
- Hank Dovey / OATK
- John Koenig
- Jacques Cuneo
- Chanse Appling
- Steve Fentress
- Bill Marshall / GRC
- Southern Research
- C-CAT
- Orbital ATK
- Materials Research and Design (MR&D)



Contact: Paul Gradl
NASA MSFC
256.544.2455
Paul.R.Gradl@nasa.gov